DUAL SPIN VALVE SENSOR WITH A LONGITUDINAL BIAS STACK

CROSS REFERENCE TO RELATED APPLICATION

U.S. patent application docket number SJO9-2001-00112US1, entitled DUAL MAGNETIC TUNNEL JUNCTION SENSOR WITH A LONGITUDINAL BIAS STACK, was filed on the same day, owned by a common assignee and having the same inventors as the present invention.

BACKGROUND OF THE INVENTION

1. Field of the Invention

This invention relates in general to spin valve magnetic transducers for reading information signals from a magnetic medium and, in particular, to a dual spin valve sensor with a longitudinal bias stack between first and second spin valve stacks of the dual sensor.

2. Description of the Related Art

Computers often include auxiliary memory storage devices having media on which data can be written and from which data can be read for later use. A direct access storage device (disk drive) incorporating rotating magnetic disks is commonly used for storing data in magnetic form on the disk surfaces. Data is recorded on concentric, radially spaced tracks on the disk

surfaces. Magnetic heads including read sensors are then used to read data from the tracks on the disk surfaces.

In high capacity disk drives, magnetoresistive (MR) read sensors, commonly referred to as MR sensors, are the prevailing read sensors because of their capability to read data from a surface of a disk at greater track and linear densities than thin film inductive heads. An MR sensor detects a magnetic field through the change in the resistance of its MR sensing layer (also referred to as an "MR element") as a function of the strength and direction of the magnetic flux being sensed by the MR layer.

The conventional MR sensor operates on the basis of the anisotropic magnetoresistive (AMR) effect in which an MR element resistance varies as the square of the cosine of the angle between the magnetization in the MR element and the direction of sense current flowing through the MR element. Recorded data can be read from a magnetic medium because the external magnetic field from the recorded magnetic medium (the signal field) causes a change in the direction of magnetization in the MR element, which in turn causes a change in resistance in the MR element and a corresponding change in the sensed current or voltage.

Another type of MR sensor is the giant magnetoresistance (GMR) sensor manifesting the GMR effect. In GMR sensors, the resistance of the MR sense layer varies as a function of the spin-dependent transmission of the conduction electrons between

magnetic layers separated by a non-magnetic spacer layer and the accompanying spin-dependent scattering which takes place at the interface of the magnetic and nonmagnetic layers and within the magnetic layers.

GMR sensors using only two layers of ferromagnetic material (e.g., Ni-Fe) separated by a layer of nonmagnetic material (e.g., copper) are generally referred to as spin valve (SV) sensors manifesting the SV effect.

Fig. **1** shows a prior art SV sensor **100** comprising end regions **104** and **106** separated by a central region **102**. A first ferromagnetic layer, referred to as a pinned (or reference) layer **120**, has its magnetization typically fixed (pinned) by exchange coupling with an antiferromagnetic (AFM) layer **125**. The magnetization of a second ferromagnetic layer, referred to as a free (or sense) layer **110**, is not fixed and is free to rotate in response to the magnetic field from the recorded magnetic medium (the signal field). The free layer **110** is separated from the pinned layer **120** by a nonmagnetic, electrically conducting spacer layer **115**. Hard bias layers **130** and **135** formed in the end regions **104** and **106**, respectively, provide longitudinal bias fields for stabilizing the free layer **110**. Leads **140** and **145** formed on hard bias layers **130** and **135**, respectively, provide electrical connections for sensing the resistance of SV sensor **100**. In the SV sensor **100**, because the sense current flow between the leads **140** and **145** is in the plane of the SV sensor

layers, the sensor is known as a current-in-plane (CIP) SV sensor. IBM's U.S. Patent No. 5,206,590 granted to Dieny et al., incorporated herein by reference, discloses a SV sensor operating on the basis of the GMR effect.

Another type of GMR sensor is an antiparallel (AP)-pinned SV sensor. The AP-pinned SV sensor differs from the simple SV sensor in that an AP-pinned structure has multiple thin film layers instead of a single pinned layer. The AP-pinned structure has an antiparallel coupling (APC) layer sandwiched between first and second ferromagnetic pinned layers. The first pinned layer has its magnetization oriented in a first direction by exchange coupling to the antiferromagnetic (AFM) pinning layer. The second pinned layer is immediately adjacent to the free layer and is antiparallel exchange coupled to the first pinned layer because of the minimal thickness (in the order of 8 Å) of the APC layer between the first and second pinned layers. Accordingly, the magnetization of the second pinned layer is oriented in a second direction that is antiparallel to the direction of the magnetization of the first pinned layer.

The AP-pinned structure is preferred over the single pinned layer because the magnetizations of the first and second pinned layers of the AP-pinned structure subtractively combine to provide a net magnetization that is much less than the magnetization of the single pinned layer. The direction of the net magnetization is determined by the thicker of the first and

second pinned layers. A reduced net magnetization equates to a reduced demagnetization field from the AP-pinned structure. Since the antiferromagnetic exchange coupling is inversely proportional to the net magnetization, this increases exchange coupling between the first pinned layer and the antiferromagnetic pinning layer. The AP-pinned SV sensor is described in commonly assigned U.S. Patent No. 5,465,185 to Heim and Parkin which is incorporated by reference herein.

Another type of magnetic device currently under development is a magnetic tunnel junction (MTJ) device. The MTJ device has potential applications as a memory cell and as a magnetic field sensor. The MTJ device comprises two ferromagnetic layers separated by a thin, electrically insulating, tunnel barrier layer. The tunnel barrier layer is sufficiently thin that quantum-mechanical tunneling of charge carriers occurs between the ferromagnetic layers. The tunneling process is electron spin dependent, which means that the tunneling current across the junction depends on the spin-dependent electronic properties of the ferromagnetic materials and is a function of the relative orientation of the magnetizations of the two ferromagnetic layers. In the MTJ sensor, one ferromagnetic layer has its magnetization fixed, or pinned, and the other ferromagnetic layer has its magnetization free to rotate in response to an external magnetic field from the recording medium (the signal field). When an electric potential is applied between the two

ferromagnetic layers, the sensor resistance is a function of the tunneling current across the insulating layer between the ferromagnetic layers. Since the tunneling current that flows perpendicularly through the tunnel barrier layer depends on the relative magnetization directions of the two ferromagnetic layers, recorded data can be read from a magnetic medium because the signal field causes a change of direction of magnetization of the free layer, which in turn causes a change in resistance of the MTJ sensor and a corresponding change in the sensed current or voltage. IBM's U.S. Patent No. 5,650,958 granted to Gallagher et al., incorporated in its entirety herein by reference, discloses an MTJ sensor operating on the basis of the magnetic tunnel junction effect.

Fig. **2** shows a prior art MTJ sensor **200** comprising a first electrode **204**, a second electrode **202**, and a tunnel barrier layer **215**. The first electrode **204** comprises a pinned layer (ferromagnetic pinned layer) **220**, an antiferromagnetic (AFM) pinning layer **230**, and a seed layer **240**. The magnetization of the pinned layer **220** is fixed through exchange coupling with the AFM layer **230**. The second electrode **202** comprises a free layer (ferromagnetic free layer) **210** and a cap layer **205**. The free layer **210** is separated from the pinned layer **220** by a nonmagnetic, electrically insulating tunnel barrier layer **215**. In the absence of an external magnetic field, the free layer **210** has its magnetization oriented in the direction shown by arrow

212, that is, generally perpendicular to the magnetization direction of the pinned layer **220** shown by arrow **222** (tail of an arrow pointing into the plane of the paper). A first lead **260** and a second lead **265** formed in contact with first electrode **204** and second electrode **202**, respectively, provide electrical connections for the flow of sensing current I_s from a current source **270** to the MTJ sensor **200**. Because the sensing current is perpendicular to the plane of the sensor layers, the MTJ sensor **200** is known as a current-perpendicular-to-plane (CPP) sensor. A signal detector **280**, typically including a recording channel such as a partial-response maximum-likelihood (PRML) channel, connected to the first and second leads **260** and **265** senses the change in resistance due to magnetization changes induced in the free layer **210** by the external magnetic field.

Two types of current-perpendicular-to-plane (CPP) sensors have been extensively explored for magnetic recording at ultrahigh densities ($\geq$ 20 Gb/in^2). One is a GMR spin valve sensor and the other is a MTJ sensor. Two challenging issues are encountered when the CPP sensor is used for ever increasing magnetic recording densities. First, the GMR coefficient may not be high enough to ensure adequate signal amplitude as the sensor width is decreased and second, magnetic stabilization of the sense layer can be difficult due to the use of insulating layers to avoid current shorting around the active region of the sensor.

A dual CPP sensor can be used to provide increased magnetoresistive response to a signal field due to the additive response of the two sensors. IBM's U.S. Patent No. 5,287,238 granted to Baumgart et al. discloses a dual CIP SV sensor. However, sensor stability still remains a major concern.

There is a continuing need to increase the GMR coefficient and reduce the thickness of GMR sensors while improving sensor stability. An increase in the GMR coefficient and reduced sensor geometry equates to higher bit density (bits/square inch of the rotating magnetic disk) read by the read head.

SUMMARY OF THE INVENTION

It is an object of the present invention to disclose a dual current-perpendicular-to-plane (CPP) spin valve (SV) sensor with improved sensor layer stabilization.

It is another object of the present invention to disclose a dual CPP SV sensor having a longitudinal bias stack between a first SV stack and a second SV stack to provide improved stabilization of the sense (free) layers of the first and second SV stacks.

It is a further object of the present invention to disclose a dual CPP SV sensor having a longitudinal bias stack comprising a first decoupling layer, a first ferromagnetic (FM1) layer, an antiferromagnetic (AFM) layer, a second ferromagnetic (FM2) layer

and a second decoupling layer disposed between the sense layers of first and second SV stacks.

It is yet another object of the present invention to disclose a dual CPP SV sensor having a longitudinal bias stack disposed between first and second SV stacks to provide three flux closures for improved sensor stability. A first flux closure provides stability of the first SV stack, a second flux closure provides stability of the second SV stack, and a third flux closure provides cancellation of demagnetizing fields from first and second antiparallel (AP)-pinned layers of the dual SV sensor.

In accordance with the principles of the present invention, there is disclosed a preferred embodiment of the present invention wherein a dual CPP SV sensor comprises a first SV stack, a second SV stack and a longitudinal bias stack disposed between first and second sense layers of the dual SV sensor. The first SV stack comprises a first antiferromagnetic (AFM1) layer, a first AP-pinned layer, a first conductive spacer layer and a first sense layer. The second SV stack comprises a second antiferromagnetic (AFM2) layer, a second AP-pinned layer, a second conductive spacer layer and a second sense layer. The longitudinal bias stack comprises a third antiferromagnetic (AFM3) layer sandwiched between a first ferromagnetic (FM1) layer and a second ferromagnetic (FM2) layer, and first and second decoupling layers in laminar contact with the FM1 and FM2 layers, respectively.

The AFM1 and AFM2 layers are set by annealing the SV sensor at elevated temperature (about 280° C) in a large magnetic field (about 10,000 Oe) oriented in a transverse direction perpendicular to an air bearing surface (ABS) to orient the magnetizations of the first and second AP-pinned layers. The AFM3 layer, formed of antiferromagnetic material having a lower blocking temperature (temperature at which the pinning field reaches zero Oe) than AFM1 and AFM2, is set by the annealing but is reset by a second annealing step at a lower temperature (about 240° C) in a much smaller magnetic field (about 200 Oe) oriented in a longitudinal direction parallel to the ABS to reorient the magnetizations of the FM1 and FM2 layers from the transverse to the longitudinal direction without reorienting magnetizations of the first and second AP-pinned layers. After the two annealing steps, the magnetizations of the first and second AP-pinned layers are oriented perpendicular to the ABS with net magnetic moments canceling each other, and the magnetizations of the FM1 and FM2 layers are oriented in the longitudinal direction. The magnetization of the FM1 layer forms a flux closure with the magnetization of the first sense layer and the magnetization of the FM2 layer forms a flux closure with the magnetization of the second sense layer. The first and second sense layers can be stabilized through magnetostatic interactions induced from the first and second flux closures, respectively.

The above as well as additional objects, features, and advantages of the present invention will become apparent in the following detailed description.

BRIEF DESCRIPTION OF THE DRAWINGS

For a fuller understanding of the nature and advantages of the present invention, as well as the preferred mode of use, reference should be made to the following detailed description read in conjunction with the accompanying drawings. In the following drawings, like reference numerals designate like or similar parts throughout the drawings.

Fig. **1** is an air bearing surface view, not to scale, of a prior art SV sensor;

Fig. **2** is an air bearing surface view, not to scale, of a prior art magnetic tunnel junction sensor;

Fig. **3** is a simplified diagram of a magnetic recording disk drive system using the dual CPP SV sensor of the present invention;

Fig. **4** is a vertical cross-section view, not to scale, of a "piggyback" read/write head;

Fig. **5** is a vertical cross-section view, not to scale, of a "merged" read/write head;

Fig. **6** is an air bearing surface view, not to scale, of a preferred embodiment of a dual CPP SV sensor according to the present invention;

Fig. **7** is an air bearing surface view, not to scale, of another embodiment of a dual CPP SV sensor according to the present invention; and

Fig. **8** is an air bearing surface view, not to scale, of an embodiment of a hybrid SV/MTJ sensor according to the present invention.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

The following description is the best embodiment presently contemplated for carrying out the present invention. This description is made for the purpose of illustrating the general principles of the present invention and is not meant to limit the inventive concepts claimed herein.

Referring now to Fig. **3**, there is shown a disk drive **300** embodying the present invention. As shown in Fig. **3**, at least one rotatable magnetic disk **312** is supported on a spindle **314** and rotated by a disk drive motor **318**. The magnetic recording media on each disk is in the form of an annular pattern of concentric data tracks (not shown) on the disk **312**.

At least one slider **313** is positioned on the disk **312**, each slider **313** supporting one or more magnetic read/write heads **321** where the head **321** incorporates the dual SV sensor of the present invention. As the disks rotate, the slider **313** is moved radially in and out over the disk surface **322** so that the heads **321** may access different portions of the disk where desired data are

recorded. Each slider **313** is attached to an actuator arm **319** by means of a suspension **315**. The suspension **315** provides a slight spring force which biases the slider **313** against the disk surface **322**. Each actuator arm **319** is attached to an actuator **327**. The actuator as shown in Fig. **3** may be a voice coil motor (VCM). The VCM comprises a coil movable within a fixed magnetic field, the direction and speed of the coil movements being controlled by the motor current signals supplied by a controller **329**.

During operation of the disk storage system, the rotation of the disk **312** generates an air bearing between the slider **313** (the surface of the slider **313** which includes the head **321** and faces the surface of the disk **312** is referred to as an air bearing surface (ABS)) and the disk surface **322** which exerts an upward force or lift on the slider. The air bearing thus counterbalances the slight spring force of the suspension **315** and supports the slider **313** off and slightly above the disk surface by a small, substantially constant spacing during normal operation.

The various components of the disk storage system are controlled in operation by control signals generated by the control unit **329**, such as access control signals and internal clock signals. Typically, the control unit **329** comprises logic control circuits, storage chips and a microprocessor. The control unit **329** generates control signals to control various system operations such as drive motor control signals on line **323**

and head position and seek control signals on line **328**. The control signals on line **328** provide the desired current profiles to optimally move and position the slider **313** to the desired data track on the disk **312**. Read and write signals are communicated to and from the read/write heads **321** by means of the recording channel **325**. Recording channel **325** may be a partial response maximum likelihood (PMRL) channel or a peak detect channel. The design and implementation of both channels are well known in the art and to persons skilled in the art. In the preferred embodiment, the recording channel **325** is a PMRL channel.

The above description of a typical magnetic disk storage system, and the accompanying illustration of Fig. **3** are for representation purposes only. It should be apparent that disk storage systems may contain a large number of disks and actuator arms, and each actuator arm may support a number of sliders.

Fig. **4** is a side cross-sectional elevation view of a "piggyback" read/write head **400**, which includes a write head portion **402** and a read head portion **404**, the read head portion employing a dual SV sensor **406** according to the present invention. The SV sensor **406** is sandwiched between ferromagnetic first and second shield layers **412** and **414** at the ABS **440**. A nonmagnetic insulating layer **409** is sandwiched between the first and second shield layers **412** and **414** in the region behind the sensor extending away from the ABS to prevent shorting between the shield layers. In response to external magnetic fields, the

resistance of the SV sensor **406** changes. A sense current I_s conducted through the sensor causes these resistance changes to be manifested as voltage changes. These voltage changes are then processed as readback signals by the processing circuitry of the data recording channel **346** shown in Fig. **3**.

The write head portion **402** of the magnetic read/write head **400** includes a coil layer **416** sandwiched between first and second insulating layers **418** and **420**. A third insulating layer **522** may be employed for planarizing the head to eliminate ripples in the second insulating layer **420** caused by the coil layer **416**. The first, second and third insulating layers are referred to in the art as an insulation stack. The coil layer **416** and the first, second and third insulating layers **418**, **420** and **422** are sandwiched between first and second pole piece layers **424** and **426**. The first and second pole piece layers **424** and **426** are magnetically coupled at a back gap **428** and have first and second pole tips **430** and **432** which are separated by a write gap layer **434** at the ABS **440**. An insulating layer **436** is located between the second shield layer **414** and the first pole piece layer **424**. Since the second shield layer **414** and the first pole piece layer **424** are separate layers, this read/write head is known as a "piggyback" read/write head.

Fig. **5** is the same as Fig. **4** except the second shield layer **514** and the first pole piece layer **524** are a common layer. This

type of read/write head is known as a "merged" head **500**. The insulation layer **436** of the piggyback head in Fig. **4** is omitted in the merged head **500** of Fig. **5**.

First Example

Fig. **6** shows an air bearing surface (ABS) view, not to scale, of a dual CPP spin valve (SV) sensor **600** according to a preferred embodiment of the present invention. The SV sensor **600** comprises end regions **604** and **606** separated from each other by a central region **602**. The seed layer **614** is a layer deposited to modify the crystallographic texture or grain size of the subsequent layers, and may not be needed depending on the subsequent layer. A first SV stack **608** deposited over the seed layer **614** comprises a first antiferromagnetic (AFM1) layer **616**, a first AP-pinned layer **617**, an conductive first spacer layer **624** and a first sense layer **625**. The first AP-pinned layer **617** is formed of two ferromagnetic layers **618** and **622** separated by an antiparallel coupling (APC) layer **620**. The APC layer is formed of a nonmagnetic material, preferably ruthenium (Ru), that allows the two ferromagnetic layers **618** and **622** to be strongly antiparallel-coupled together. The AFM1 layer **616** has a thickness at which the desired exchange properties are achieved, typically 100-300 Å.

A longitudinal bias stack **610** sequentially deposited over the first SV stack **608** comprises a first decoupling layer **629**, a first ferromagnetic (FM1) layer **630**, a third antiferromagnetic (AFM3) layer **632**, a second ferromagnetic (FM2) layer **634** and a second decoupling layer **633**. A second SV stack **612** deposited over the longitudinal bias stack **610** comprises a second sense layer **639**, a second conductive spacer layer **640**, a second AP-pinned layer **641** and a second antiferromagnetic (AFM2) layer **648**. The second AP-pinned layer **641** is formed of two ferromagnetic layers **642** and **646** separated by an antiparallel coupling (APC) layer **644**. The APC layer is formed of a nonmagnetic material, preferably ruthenium (Ru), that allows the two ferromagnetic layers **642** and **646** to be strongly anti-parallel coupled together. The AFM2 layer **648** has a thickness at which the desired exchange properties are achieved, typically 100-300 Å. A cap layer **650**, formed on the AFM2 layer **648**, completes the central region **602** of the dual SV sensor **600**.

The AFM1 layer **616** is exchange-coupled to the first AP-pinned layer **617** to provide a pinning field to pin the magnetizations of the two ferromagnetic layers of the first AP-pinned layer perpendicular to the ABS as indicated by an arrow tail **619** and an arrow head **623** pointing into and out of the plane of the paper, respectively. The first sense layer **625** has a magnetization **627** that is free to rotate in the presence of an

external (signal) magnetic field. The magnetization **627** of the first sense layer **625** is preferably oriented parallel to the ABS in the absence of an external magnetic field.

The AFM2 layer **648** is exchange coupled to the second AP-pinned layer **641** to provide a pinning magnetic field to pin the magnetizations of the two ferromagnetic layers of the second AP-pinned layer perpendicular to the ABS as indicated by an arrow head **643** and an arrow tail **645** pointing out of and into the plane of the paper, respectively. The second sense layer **639** has a magnetization **637** that is free to rotate in the presence of an external (signal) magnetic field. The magnetization **637** of the second sense layer **639** is preferably oriented parallel to the ABS in the absence of an external magnetic field.

The AFM3 layer **632** is exchange coupled to the FM1 layer **630** and the FM2 layer **634** to provide pinning fields to pin the magnetizations **631** and **635**, respectively, parallel to the plane of the ABS. The magnetizations **631** and **635** provide longitudinal bias fields which form flux closures with the first and second sense layers **625** and **639**, respectively, to stabilize the first and second sense layers **625** and **639**.

First and second shield layers **652** and **654** adjacent to the seed layer **614** and the cap layer **650**, respectively, provide electrical connections for the flow of a sensing current I_s from a current source **660** to the SV sensor **600**. A signal detector **670**

which is electrically connected to the first and second shield layers **652** and **654** senses the change in resistance due to changes induced in the sense layers **625** and **639** by the external magnetic field (e.g., field generated by a data bit stored on a disk). The external field acts to rotate the magnetizations of the sense layers **625** and **639** relative to the magnetizations of the pinned layers **622** and **642** which are preferably pinned perpendicular to the ABS. The signal detector **670** preferably comprises a partial response maximum likelihood (PRML) recording channel for processing the signal detected by SV sensor **600**. Alternatively, a peak detect channel or a maximum likelihood channel (e.g., 1,7 ML) may be used. The design and implementation of the aforementioned channels are known to those skilled in the art. The signal detector **670** also includes other supporting circuitries such as a preamplifier (electrically placed between the sensor and the channel) for conditioning the sensed resistance changes as is known to those skilled in the art.

The SV sensor **600** is fabricated in an integrated ion beam/DC magnetron sputtering system to sequentially deposit the multilayer structure shown in Fig. **6**. The sputter deposition process is carried out in the presence of a longitudinal magnetic field of about 40 Oe. The first shield layer **652** formed of Ni-Fe having a thickness of 10000 Å is deposited on a substrate **601**. The seed layer **614** is a bilayer with a first sublayer of tantalum (Ta) having a thickness of 30 Å and a second sublayer of Ni-Fe

having a thickness of 10 Å deposited on the first shield layer **652**. The first SV stack **608** is formed on the seed layer by sequentially depositing the AFM1 layer **616** of Pt-Mn having a thickness of about 160 Å, the ferromagnetic layer **618** of Co-Fe having a thickness of about 12 Å, the APC layer **620** of ruthenium (Ru) having a thickness of about 8 Å, the ferromagnetic layer **622** of Co-Fe having a thickness of about 18 Å, the conductive first spacer layer **624** of Cu-O having a thickness of about 22 Å, and the first sense layer **625** of Co-Fe having a thickness of about 18 Å. The first spacer layer **624** is formed by depositing a copper (Cu) film with DC-magnetron sputtering from a pure Cu target in a mixture of argon and oxygen gases of 2.985 and 0.015 mTorr, respectively, and then exposing to a mixture of argon and oxygen gases of 2.94 and 0.06 mTorr, respectively, for 4 minutes. This optimum *in situ* oxidation is incorporated into this Cu-O formation process for reducing ferromagnetic coupling between the sense and pinned layers.

The longitudinal bias stack **610** is formed on the first SV stack **608** by sequentially depositing the first decoupling layer **629** comprising a first sublayer **626** of Cu-O having a thickness of about 10 Å and a second sublayer **628** of ruthenium (Ru) having a thickness of about 20 Å, the FM1 layer **630** of Co-Fe having a thickness of about 24 Å, the AFM3 layer **632** of Ir-Mn having a thickness of about 60 Å, the FM2 layer **634** of Co-Fe having a

thickness of about 24 Å, and the second decoupling layer **633** comprising a first sublayer **636** of ruthenium (Ru) having a thickness of about 20 Å and a second sublayer **638** of Cu-O having a thickness of about 10 Å. The Cu-O sublayers **626** and **638** are formed by depositing a copper (Cu) film with DC-magnetron sputtering from a pure Cu target in a mixture of argon and oxygen gases of 2.985 and 0.015 mTorr, respectively, and then exposing to a mixture of argon and oxygen gases of 2.94 and 0.06 mTorr, respectively, for 4 minutes. The Cu-O films facilitate the sense layers to exhibit good soft magnetic properties.

The second SV stack **612** is formed on the longitudinal bias stack **610** by sequentially depositing the second sense layer **639** of Co-Fe having a thickness of about 18 Å, the conductive second spacer layer **640** of Cu-O having a thickness of about 22 Å, the ferromagnetic layer **642** of Co-Fe having a thickness of about 18 Å, the APC layer **644** of ruthenium (Ru) having a thickness of about 8 Å, the ferromagnetic layer **646** of Co-Fe having a thickness of about 12 Å, and the AFM2 layer **648** of Pt-Mn having a thickness of about 160 Å. The spacer layer **640** is formed by depositing a copper (Cu) film with DC-magnetron sputtering from a pure Cu target in a mixture of argon and oxygen gases of 2.985 and 0.015 mTorr, respectively, and then exposing to a mixture of argon and oxygen gases of 2.94 and 0.06 mTorr, respectively, for 4 minutes. This optimum *in situ* oxidation is incorporated into

this Cu-O formation process for reducing ferromagnetic coupling fields between the sense and pinned layers. The cap layer **650** is a bilayer with a first sublayer of ruthenium (Ru) having a thickness of 40 Å and a second sublayer of tantalum (Ta) having a thickness of 30 Å formed over the AFM2 layer **648**.

The second shield layer **654** formed of Ni-Fe having a thickness of 10000 Å is deposited over the cap layer **650**. An insulating layer **656** formed of Al_2O_3 deposited between the first shield layer **652** and the second shield layer **654** provides electrical insulation between the shields/leads and prevents shunting of the sense current around the active region **602** of the dual SV sensor **600**.

After the deposition of the central portion **602** is completed, the SV sensor is annealed for 2 hours at 280° C in the presence of a magnetic field of about 10,000 Oe in a transverse direction perpendicular to the ABS and is then cooled while still in the magnetic field to set the exchange coupling of the AFM1 and AFM2 layers **616** and **648** with the AP-pinned layers **617** and **641**, respectively, so that the magnetizations in the two AP-pinned layers are perpendicular to the ABS with net magnetic moments canceling each other. This results in cancellation of the demagnetization fields between the the AP-pinned layers **617** and **641**.

After the first anneal, a second anneal is carried out for 2 hours at 240° C in the presence of a magnetic field of 200 Oe in a longitudinal direction parallel to the ABS. Because the blocking temperature of the Pt-Mn antiferromagnetic material (> 360° C) of the AFM1 and AFM2 layers is higher than 240° C, the magnetizations of the first and second AP-pinned layers **617** and **641** are not rotated while the magnetizations **631** and **635** in the longitudinal bias stack are oriented in the longitudinal direction due to the lower (less than 240° C) blocking temperature of the Ir-Mn antiferromagnetic material of the AFM3 layer. After the second anneal, the magnetization **631** of the FM1 layer **630** forms a flux closure with the magnetization **627** of the first sense layer **625** providing stability for the first sense layer **625**. Similarly, the magnetization **635** of the FM2 layer **634** forms a flux closure with the magnetization **637** of the second sense layer **639** providing stability of the second sense layer **639**.

The Cu-O/Ru and Ru/Cu-O films are used as first and second decoupling layers **629** and **633**. Either one of the Cu-O or Ru films is not used alone as a decoupling layer since strong exchange coupling occurs across either film and full decoupling can only be attained when the film thickness is far greater than 30 Å. In order to attain strong magnetostatic interactions from the flux closures, the decoupling layer thickness is preferred to

be as small as possible, but not to be too small to induce the exchange coupling. The Cu-O film of the decoupling layers is adjacent to the Co-Fe sense layers to promote good soft magnetic properties. The Ru film of the decoupling layers is also used as a seed layer for the Co-Fe/Ir-Mn/Co-Fe longitudinal bias layers to promote high unidirectional anisotropy fields (H_{UA}).

In this preferred embodiment, the Co-Fe/Ir-Mn/Co-Fe film stack is used for antiferromagnetic stabilization of the dual SV sensors. Alternatively, a Ni-Fe(10Å)/Co-Pt(40Å)/Ni-Fe(10Å) film stack can be used to replace the Co-Fe/Ir-Mn/Co-Fe film stack for hard magnetic stabilization. The Ni-Fe film is adjacent to the Co-Pt film in order to reduce stray fields from the Co-Pt film and improve its squareness. In this alternate embodiment, the second anneal used to longitudinally orient the magnetizations of the Co-Fe/Ir-Mn/Co-Fe stack is eliminated, but magnetic setting of the Ni-Fe/Co-Pt/Ni-Fe stack in a field of 3 kOe must be conducted at room temperature after the head fabrication process.

Second Example

Fig. **7** shows an air bearing surface (ABS) view, not to scale, of a CPP dual spin valve (SV) sensor **700** according to another embodiment of the present invention. The dual SV sensor **700** is the same as the dual SV sensor **600** shown in Fig. **6** except that in order to achieve a read gap thickness of 50 nm the AFM1 and AFM2 layers **616** and **648** have been eliminated and the AFM3

layer **632** of the longitudinal bias stack **610** has been replaced by an AFM3 layer **716** of Pt-Mn having a thickness of 160 Å. The dual SV sensor **700** comprises a first SV stack **708**, a second SV stack **712** and a longitudinal bias stack **710** disposed between the first and second SV stacks **708** and **712**. In this embodiment the first SV stack **708** is the same as SV stack **608** without the AFM1 layer **616** and the second SV stack **712** is the same as SV stack **612** without the AFM2 layer **648**. The longitudinal bias stack **710** is the same as bias stack **610** with the AFM3 layer of Ir-Mn replaced with an AFM3 layer **716** of Pt-Mn having a thickness of 160 Å.

The SV sensor **700** is fabricated in an integrated ion beam/DC magnetron sputtering system to sequentially deposit the multilayer structure shown in Fig. **7**. The deposition process is the same as the process used to fabricate the SV sensor **600**.

After the deposition of the central portion **602** is completed, the SV sensor **700** is annealed for 2 hours at 280° C in the presence of a magnetic field of 200 Oe in a longitudinal direction parallel to the ABS. The magnetic field is higher than the uniaxial anisotropy field H_K (≤ 20 Oe) of the as-deposited Co-Fe/Pt-Mn/Co-Fe films so that strong exchange coupling in the Co-Fe/Pt-Mn/Co-Fe films can be developed in the longitudinal direction parallel to the ABS during annealing. The magnetic field is less than the spin flop field H_{SF} (≥ 1 kOe) of the first and second AP-pinned layers **617** and **641** so that strong

antiparallel coupling across the Ru APC layers in the first and second AP-pinned layers **617** and **641** is not interrupted during annealing.

Although the Pt-Mn AFM layers are not used in the first and second SV stacks **708** and **712** to produce H_{UA} for transverse pinning, the transverse pinning can still be attained due to a strong spin-flop field (H_{SP}) induced from antiparallel coupling across the Ru APC layers. The transverse pinning can be further reinforced if the Co-Fe films adjacent to the Ru APC layers have a high intrinsic uniaxial anisotropy field (H_K) and a high positive saturation magnetostriction (λ_S). The high λ_S is needed to stress-induce a high extrinsic uniaxial anisotropy field (H_K'), determined from $H_K' = 3(\lambda_S/M_S)\sigma$ after sensor lapping. The Co_{90}-Fe_{10} (in atomic %) commonly used for the ferromagnetic layers of the AP-pinned layers **617** and **641** has an H_K of 16 Oe. When the Fe content is increased to 20 at.%, H_K becomes 30 Oe and the λ_S increases to 35.1 x 10^{-6} (corresponding to 142 Oe). Hence, in this alternative embodiment, a Co-Fe film with an Fe content of 20 at.% or higher (up to 50 at.%) is preferably used for the ferromagnetic layers of the AP-pinned layers.

Although the total uniaxial anisotropy field $H_K + H_K'$(172.5 Oe) is not as high as H_{UA} (600 Oe) and H_{SP} (900 Oe), it has two major unique features, leading it to play an important role in providing transverse pinning. First, $H_K + H_K'$ is determined only from the Co-Fe film itself, while H_{UA} and H_{SP} are determined not

only from the Co-Fe film, but also from its adjacent Ru and Pt-Mn films. As a result, the temperature dependence of $H_K + H_K'$ is determined by the Curie temperature of the Co-Fe film (~700 °C), while the temperature dependence of H_{UA} is determined by the blocking temperature of the exchange-coupled Pt-Mn/Co-Fe films (~360 °C), and the temperature dependence of H_{SP} is determined by the critical temperature of the antiparallel-coupled Co-Fe/Ru/Co-Fe films. Since the Curie temperature is much higher than the blocking and critical temperatures, $H_K + H_K'$ can remain nearly unchanged at elevated sensor operation temperatures (~180 °C). Thus $H_K + H_K'$ may play a crucial role in improving thermal stability. Second, $H_K + H_K'$ substantially reduces edge curling effects of magnetizations of the ferromagnetic films of the AP-pinned layers. The reduction in the edge curling effects results in more uniform magnetization along the sensor height, therefore providing better flux closure to cancel magnetization more efficiently. Hence, even without the use of the Pt-Mn film for transverse pinning, the transverse pinning field resulting from H_{SP}, H_K and H_K' should be high enough for proper sensor operation.

Third Example

Fig. **8** shows an air bearing surface (ABS) view, not to scale, of a CPP hybrid spin valve (SV)/magnetic tunnel junction (MTJ) sensor **800** according to a another embodiment of the present

invention. The hybrid SV/MTJ sensor **800** is the same as the dual SV sensor **600** shown in Fig. **6** except that one of the two SV stacks **608** and **612** is replaced with a magnetic tunnel junction (MTJ) stack. In the embodiment shown in Fig. **8**, the second SV stack **612** has been replaced with an MTJ stack **812**. However, alternatively, the first SV stack **608** may be replaced with an MTJ stack to form an alternative hybrid MTJ/SV sensor.

The SV/MTJ sensor **800** comprises an SV stack **608**, an MTJ stack **812** and a longitudinal bias stack **610** disposed between the SV stack **608** and and the MTJ stack **812**. In this embodiment the SV stack **608** and the longitudinal bias stack **610** are identical to the first SV and longitudinal bias stacks of the preferred embodiment shown in Fig. **6**. The MTJ stack **812** deposited over the longitudinal bias stack **610** comprises a second sense layer **639**, a nonconductive tunnel barrier layer **840**, a second AP-pinned layer **641** and a second antiferromagnetic (AFM2) layer **648**. Only the tunnel barrier layer **840** which replaces the conductive second spacer layer **640** of the SV sensor **600** is different from the layers forming the SV sensor **640**. The tunnel barrier layer **840** of Al-O having a thickness of about 6 Å is formed on the second sense layer **639** by depositing an aluminum (Al) film with DC-magnetron sputtering from a pure Al target in an argon gas of 3 mTorr, and then exposing to an oxygen gas of 2 Torr for 4 minutes. This optimal *in situ* oxidation is incorporated into

this Al-O formation process for attaining a high tunneling magnetoresistance and a low junction resistance. The second AP-pinned layer **641** and the AFM2 layer **648** are sequentially deposited on the tunnel junction layer **840** to complete the fabrication of the MTJ stack **612**. All other processing steps are identical to those described above with respect to fabrication of the SV sensor **600**. The response of the hybrid dual SV/MTJ sensor **800** to an external magnetic signal is the sum of the response of the SV stack **608** and the response of the MTJ stack **812**.

Alternatively, for the hybrid MTJ sensor **800**, the AFM1 and AFM2 layers formed of Pt-Mn used in the first and second stacks can be eliminated, and the Ir-Mn film used for AFM3 in the longitudinal bias stack may also be replaced with a Pt-Mn film as described in the second example.

While the present invention has been particularly shown and described with reference to the preferred embodiments, it will be understood by those skilled in the art that various changes in form and detail may be made without departing from the spirit, scope and teaching of the invention. Accordingly, the disclosed invention is to be considered merely as illustrative and limited only as specified in the appended claims.